RES 17-06

M E M O R A N D U M

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DATE: December 12, 2003

SUBJECT: Review of Methods for Long-Term (1965-2000) Solar Radiation and Potential Evapotranspiration Estimation for Hydrologic Modeling in South Florida

Evapotranspiration is one of the main hydrologic variables in South Florida, second only to rainfall. Since evapotranspiration and rainfall are very similar in magnitude in South Florida, the balance between the two variables dictates water availability in the system. Therefore, it is important to obtain reliable estimates of the two variables for hydrologic modeling. Solar radiation has been found to account for approximately 75% of the variability in evapotranspiration in South Florida. Therefore, solar radiation estimation is key in estimating potential or reference evapotranspiration in South Florida. This memorandum examines and compares several methods for estimating solar radiation and potential evapotranspiration over South Florida. The methodology selected for estimating solar radiation and potential evapotranspiration for long-term hydrologic modeling is explained in detail.

Introduction:

Potential evapotranspiration (ET_p) has been defined by Penman (1956) as "the amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height and never short of water." Any short green crop is implied in this definition. However, for practical purposes it is usually hard and expensive to measure or estimate ET_p for several different crops. Therefore, the potential evapotranspiration for a well-watered reference crop such as alfalfa or short-grass has been used as a reference and defined as reference evapotranspiration. Crop coefficients are applied to link the potential evapotranspiration of a specific crop to either grass (ET_o) or alfalfa (ET_r) reference evapotranspiration. These crop-specific coefficients can be obtained by calibration from field measurements and typical values are recorded in the literature (ASCE, 1990; Allen et al., 1998).

Long-term daily (1965-2000) potential or reference evapotranspiration at several sites is required as input to the South Florida Water Management Model (SFWMM) and the Natural System Model (NSM). In these models, actual evapotranspiration is calculated by spatial interpolation of the reference or potential evapotranspiration between the sites, and by the application of landscape-specific crop coefficients that are a function of water depth. Several potential methods for estimating potential or reference evapotranspiration for use in these regional long-term continuous simulation models are examined in the next section. Then the selected method for ET_p estimation is presented in detail.

Potential/Reference Evapotranspiration Estimation Methods:

1. Penman-Monteith:

The Penman-Monteith method (Monteith, 1981), which combines energy balance and mass transfer methods, has been used extensively in both arid and humid climates to provide estimates of evapotranspiration and is defined by Equation 1:

$$ET = \frac{\Delta(R_n - G) + \rho c_p (e_a - e_d) 1/r_a}{\lambda[\Delta + \gamma(1 + r_c / r_a)]} \tag{1}$$

where

ET	:	evapotranspiration	[mm d^{-1}]
Δ	:	slope saturated vapor pressure-temperature curve at mean air temperature	[kPa °C^{-1}]
γ	:	psychrometric constant	[kPa °C^{-1}]
R_n	:	net radiation	[MJ m^{-2} d^{-1}]
G	:	soil heat flux	[MJ m^{-2} d^{-1}]
λ	:	latent heat of evaporation	[MJ kg^{-1}]
c_p	:	specific heat of moist air	[kJ kg^{-1} °C]
ρ	:	atmospheric density	[kg m^{-3}]
c_p	:	specific heat of moist air	[kJ kg^{-1} °C]
e_a	:	saturation vapor pressure at mean air temperature	[kPa]
e_d	:	saturation vapor pressure at dew point temperature (T_{dew})	[kPa]
r_c	:	crop canopy (bulk stomata) resistance	[s m^{-1}]
r_a	:	aerodynamic resistance	[s m^{-1}]

The Penman-Monteith method depends on many variables that are usually hard to measure or estimate accurately for different crops (see Appendix A for more details). For practical purposes, Penman-Monteith is used to estimate grass (ET_o) or alfalfa (ET_r) reference evapotranspiration. The Food and Agricultural Organization of the United Nations (FAO: Smith, 1991) provides guidelines for the estimation of many of these variables for a well-watered reference grass of 12 cm in height. Standard assumptions for a 12-cm reference grass are summarized in Appendix A; however some critical variables and problems associated with estimating these variables in South Florida are described in more detail in the next sections.

a) Solar radiation

Incoming solar (shortwave) radiation (R_s) is an important component of the energy balance at the land surface. Approximately 75% (R=0.73) of the variability of daily evapotranspiration in South Florida is explained by solar radiation (Abtew, 1996). Long-term (1965-2000) daily measurements of solar radiation in South Florida are very scarce.

The only long-term (1961-1985) dataset of measured R_s that could be found is the SAMSON dataset (NREL, 1993) for Miami International Airport. The SAMSON dataset also includes estimates of R_s at Key West and West Palm Beach based on cloud cover. Additional R_s data has been collected by the SFWMD for relatively short periods of time at several stations. Several methods for estimating historical solar radiation are presented in a separate section.

b) Dew point temperature

Long-term (1965-2000) measurements of daily dew point temperature (T_{dew}) for South Florida are very sparse. Several relationships for patching T_{dew} have been developed. Most of these relationships are based on daily minimum temperature (T_{min}) measurements and have the form $T_{dew}=T_{min}-\Delta T$. An expert consultation (FAO: Smith, 1991) suggests that when no measured data is available, T_{min} may be an acceptable estimate for T_{dew} (i.e. $\Delta T=0$) in humid climates. This is consistent with the strong relationship of $T_{dew}=T_{min}-1$ (i.e. $\Delta T=1$) found for Fort Myers based on regression analysis of T_{dew} and T_{min} measurements (Tarboton and Kumar, 1998).

Based on T_{dew} and T_{min} measurements at Miami and West Palm Beach international airports, monthly values of ΔT were obtained by minimizing the sum of the errors squared between the measured T_{dew} and the estimated T_{dew} ($=T_{min}-\Delta T$). Figure 1 shows that ΔT for these stations exhibits strong seasonal and spatial variability with mean annual values of ΔT ranging from about 1.8 to 3.6 ºF. Our findings do not necessarily invalidate FAO (Smith, 1991) or Tarboton and Kumar (1998) findings, but may just reflect different geographical regions for which these relationships were developed.

Monthly-varying values of ΔT reflect seasonal differences in the atmosphere's water-holding capacity. However, using long-term monthly values of ΔT on average much greater than 1, resulted in a relatively high estimate of ET_o (36-yr average ET_o at Miami International Airport: 59.2 in/yr) when using the Penman-Monteith equation with temperature-based solar radiation (see section on solar radiation estimation methods). When the relationship $T_{dew} = T_{min}$ was used, the estimated ET_o was approximately 10% lower (36-yr average ET_o at Miami International Airport: 52.5 in/yr) and closer to estimates of potential evapotranspiration found in literature (Visher and Hughes, 1969; Waylen and Zorn, 1998). These findings indicate that the estimated ET_o is very sensitive to the dew point temperature (Tdew). This is consistent with Abtew's (1996) findings that vapor pressure deficit has the largest correlation with daily evapotranspiration (R=0.59) next to solar radiation (R=0.73). The fact that more accurate estimate of T_{dew} (i.e. long-term monthly mean ΔT values from Figure 1) resulted in estimates of ET_o which were higher than those values of ET_o found in the literature, suggests that there may be problems in the estimation of other variables used in the Penman-Monteith method.

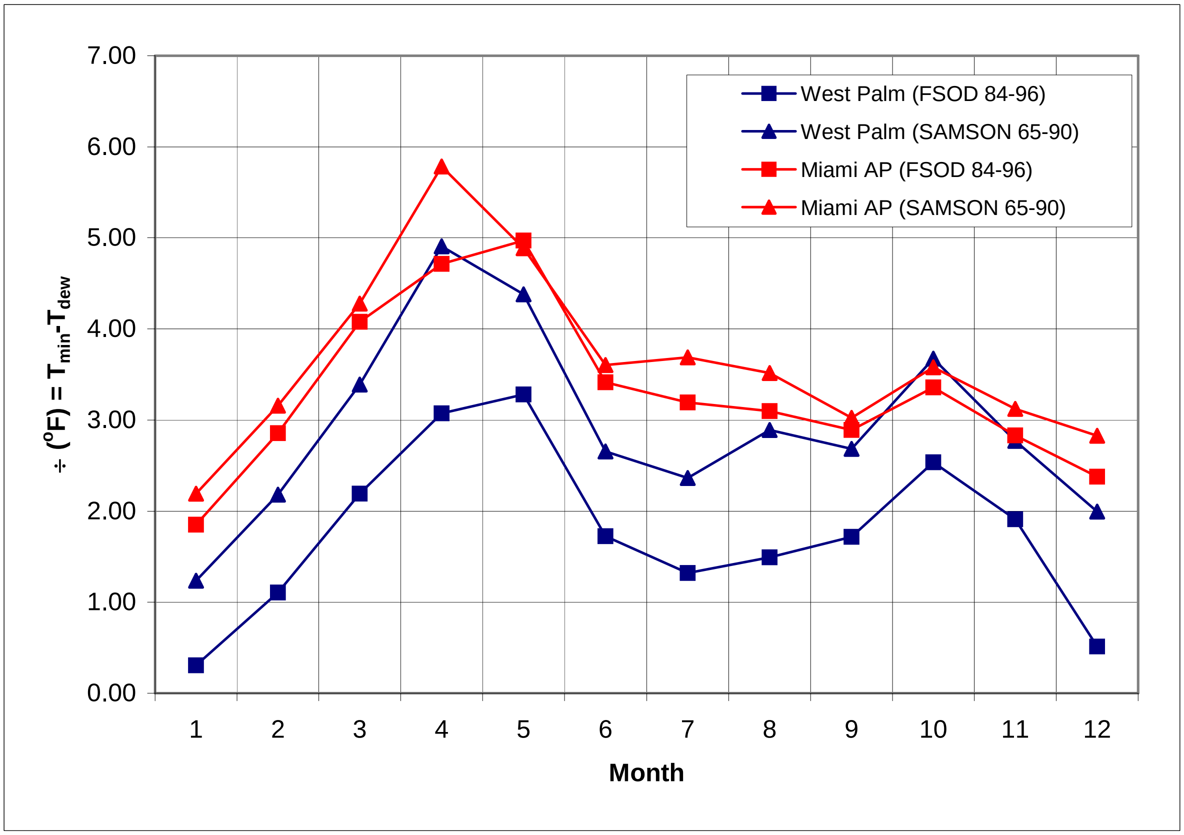


Figure 1. Differences between monthly average minimum daily air and dew point temperatures for Miami and West Palm Beach International Airports ($\Delta T = T_{min} - T_{dew}$) in degrees Fahrenheit. SAMSON = Solar and Meteorological Surface Observation Network (NREL, 1993). FSOD = NOAA First Summary of the Day (France, 1998).

c) Wind speed

The application of Penman-Monteith on a daily basis requires daily measurements of wind speed (U_z). Surface roughness characteristics and wind speed measurement height are used to define a typical logarithmic wind profile, which is required for the quantification of aerodynamic resistance to evapotranspiration (Appendix A, Equation A-11).

Long-term (1965-2000) measurements of wind speed for South Florida are scarce, with available wind data from several sources summarized in Appendix B.

Wind speed can vary significantly from day to day. However, due to the lack of long-term (1965-2000) daily wind speed at several stations, long-term mean monthly wind speed data was used in the Penman-Monteith method. Information such as changes in tower height with time and changes in surface cover is needed to calculate the long-term mean monthly wind speed at a certain height. During the process of collating wind speed data it became obvious that wind speed is measured at different heights for different stations. Furthermore, the tower height and location can change in time for a particular station as is the case with SAMSON stations. Since this information was not readily available for GSOD (NCDC) stations, the long-term mean wind speed was only calculated at several SFWMD DBHydro (<10 years of data) and SAMSON (1961-1990) stations. Figure 2 shows that in general, mean monthly wind speed is higher at Lake Okeechobee (L001, L002) and coastal stations (Miami, WPB), and lowest at interior stations. Although different periods of record are being compared, the higher coastal wind speeds are consistent with wind class definitions for South Florida, i.e. coastal winds between 9.8 and 11.5 mph, and interior winds between 0 and 9.8 mph at 33 ft (NREL, 1986).

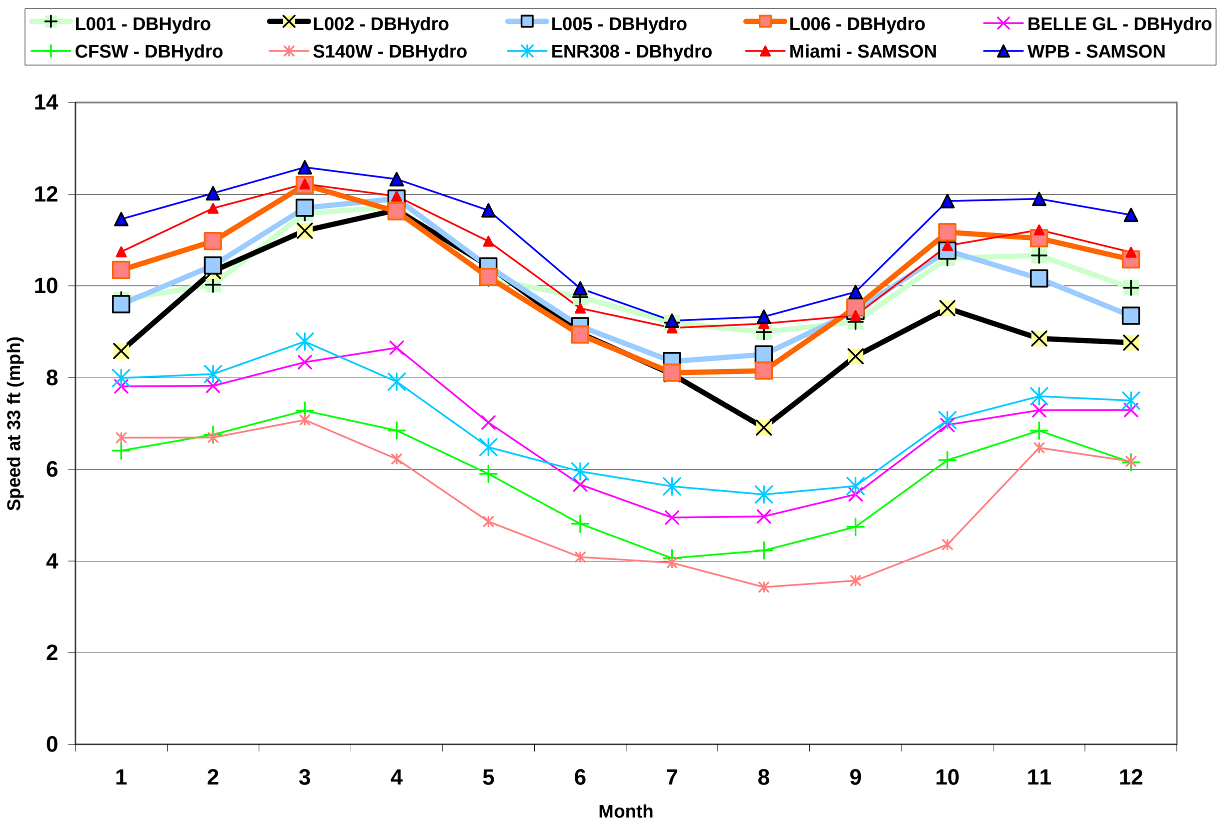


Figure 2. Long-term mean monthly wind speed at 33 ft from several sources. SAMSON data is long-term mean for the period 1961-1990 and has been converted to 33 ft. DBHydro data is long-term mean for less than 10 years of data.

d) Reference crop parameters

FAO's definition of the reference crop is very specific and this hypothetical crop may not even exist in the field. Standard assumptions for a 12 cm well-watered grass reference crop are given in Table 1.

Boundary layer and eddy diffusivity concepts in Penman-Monteith, require that all measurements be taken above a crop with essentially the same characteristics as the reference crop. However, in practice this is usually not the case. Meteorological measurements are frequently taken at airports and at other sites with a different surface cover from the reference crop. If measurements are taken above a different surface from the reference crop, corrections to the measurements are required to insure accurate estimates of reference crop evapotranspiration (ET_o). These corrections are usually empirical and are therefore hard to quantify due to the lack of data.

A more representative ‘reference crop’ for South Florida than the FAO reference grass, is an inundated marsh. Abtew (1995, 1996) undertook a lysimeter evapotranspiration study that quantified potential evapotranspiration for a South Florida marsh and enabled comparison of measured potential ET with Penman-Monteith estimated reference ET.

Important meteorological variables (e.g. air temperature, barometric pressure, relative humidity, leaf wetness, water temperature, net and solar radiation, wind and rainfall) were measured between 1993 and 1995 at SFWMD's ENR308 station as part of the lysimeter evapotranspiration study. Since the marsh site was kept inundated, the annual average measured ET (1994-1995) of 50 inches/year should be representative of potential evapotranspiration for a South Florida marsh. The Penman-Monteith equation with crop parameters (Table 1) estimated by Abtew (1995) was compared with other ET estimation methods and was found to give the most accurate estimates of the measured ET at the site.

Using meteorological data at ENR308, the Penman-Monteith estimated ET_o, for a standard reference grass with crop parameters as defined by FAO (Table 1, Appendix A) was 72 inches per year. The large discrepancy between the two Penman-Monteith estimates is due to the different assumptions in crop-specific parameters as summarized in Table 1.

It is obvious that ET estimates that are far from the potential ET observed in South Florida can be obtained depending on the parameters assumed when applying the Penman-Monteith equation. In order to match potential ET measurements at ENR308, an average coefficient of 0.7 = 50/72 would have to be applied to the grass-reference ET.

Table 1. Comparison of FAO standard and inundated marsh crop parameters.

Variable	FAO standard assumption for a 12-cm well-watered reference grass	Inundated marsh at ENR308 (W. Abtew, 1995)
r_a	All parameters assumed fixed during the year: h_c = 0.12 m for a grass reference crop d = (2/3) * h_c = 0.08 m z_{om} = 0.123 * h_c = 0.015 m z_{oh} = 0.1 * z_{oh} = 0.0015 m	F_c and h_c vary seasonally, d varies seasonally: d=0.85* F_c * h_c. average F_c ~ 0.8 average h_c ~ 1.6 average d ~ 1.1 z_{om} = 0.13 *(h_c -d) average z_{om} ~ 0.065 m z_{oh} = 0.1* z_{om} average z_{oh} ~ 0.0065 m
r_c	LAI = 24* h_c = 2.88 r_c = 200/LAI = 200/2.88 = 70 s/m	Seasonally varying r_c based on seasonal stomatal resistance and LAI. r_c during the high ET season (days of year 129-288) = 25 s/m r_c during the rest of the year = 90 s/m
α	α = 0.23	average α ~ 0.17

h_c : average crop height
F_c : fractional vegetation cover
d : zero plane displacement of wind profile = f(hc,Fc)
z_{om} : surface roughness length for momentum transfer = f(hc,d)
z_{oh} : surface roughness length for heat and vapor transfer
LAI : leaf area index
r_a : aerodynamic resistance = f(zom,zoh,d)
r_c : canopy or bulk stomatal resistance
α : albedo

The Penman-Monteith equation is most accurate when used for short time steps on the order of an hour and the values summed to estimate the daily ET (ASCE, 1990). However, in practice usually only daily total or mean values of meteorological parameters are available. FAO (Smith, 1991) and ASCE (ASCE, 1990) provide guidelines for performing calculations (e.g. net longwave radiation, vapor pressure) using daily meteorological parameters to insure that reliable estimates of ET are obtained when using Penman-Monteith.

Due to the lack of a comprehensive meteorological database for South Florida, the many assumptions going into the FAO definition of the reference crop and the need for meaningful estimates of reference or potential ET that are closed to the observed potential ET in South Florida, a simpler yet equally accurate method for estimating potential ET is required.

2. SFWMD Simple Method:

Approximately 75% (R=0.73) of the variability of daily evapotranspiration in South Florida is explained by solar radiation (Abtew, 1996). Therefore, a simple potential ET estimation method with R_s as the only variable is a viable alternative to Penman-Monteith. As demonstrated by Abtew (1996), the SFWMD Simple Method (Equation 2) can provide accurate estimates of potential ET for cattails and wet marsh vegetation with coefficients of determination (R^2) at ENR308 close to those obtained with the Penman-Monteith equation.

$$ET_p = \frac{K_1 * R_s}{\lambda} \tag{2}$$

ET_p:	wet marsh potential evapotranspiration		[mm d^{-1}]
K_1 :	coefficient (0.53 for mixed marsh, open water and shallow lakes)		
R_s :	solar radiation received at the land surface		[MJ m^{-2} d^{-1}]
λ :	latent heat of evaporation		[MJ kg^{-1}]

Due to its simplicity, the Simple Method can be used to provide estimates of long-term historical (1965-2000) *wet marsh potential ET* for long-term hydrological modeling. It is important to keep in mind that the empirical coefficient K_1 in Equation 2 has been calibrated to 0.53 for wet marsh, open water and shallow lakes. Therefore, in order to avoid confusion it is important to make a distinction between a grass-reference ET (ET_o) and wet marsh potential ET (ET_p) estimated using the Simple Method. Due to the difference in roughness characteristics between marsh and reference grass surfaces, the crop coefficients developed with respect to a grass-reference ET may need to be modified for use with wet marsh potential ET.

A recent enhancement to the SFWMD DBHydro database is the computation (Reardon and Abtew, 2002) of potential ET using six different methods including the Simple Method. As meteorological data becomes available, *wet marsh potential ET* estimates using the Simple Method at eleven stations across the SFWMD will be loaded into the SFWMD DBHydro database for District-wide and general public access. Use of the Simple Method to estimate long-term wet marsh potential ET for hydrological modeling provides consistency with up-to-date estimates available on-line through DBHydro.

The use of the Simple Method does not entirely solve the problem of lack of meteorological data for potential ET estimation in South Florida. Solar radiation measurements or a method for estimating R_s when it is not measured is still required.

Solar Radiation Estimation Methods:

Long-term (1965-2000) daily measurements of solar radiation (R_s) in South Florida are very scarce. The only long-term (1961-1985) dataset of measured R_s that could be found is the SAMSON dataset for Miami International Airport. Additional R_s data has been collected by the SFWMD for relatively short periods of time at several stations (Olthoff, 1999). Several methods for estimating solar radiation from other meteorological data are discussed next.

1. Cloud cover

Clear-sky solar radiation (R_{so}) is decreased by cloud cover, atmospheric dust, smoke and aerosol content. This decrease in R_{so} can be quantified from measurements of percentage sunshine. Several linear relationships relating R_s to the percentage of sunshine amount or hours (S or n/N) and clear-sky (R_{so}) or extraterrestrial radiation (R_a) have been developed (ASCE, 1990; Restrepo et al., 1995). However, in the absence of percentage sunshine data, measurements of sky cover and atmospheric content have traditionally been used to generate irradiance data. As an example, the SAMSON dataset includes long-term estimates of R_s at several stations in South Florida (Key West 1961-1990, West Palm Beach 1961-1990, Miami International Airport 1985-1990) based on cloud cover and aerosol optical depth.

Cloud cover usually has the largest influence on solar radiation. Therefore, in the absence of atmospheric content information, cloud cover measurements or observations can generally provide reasonable estimates of R_s. As an example, Restrepo et al. (1995) developed the following equation to estimate percentage of actual to possible (n/N) sunshine hours based on cloud cover information:

$$\frac{n}{N} = 0.95 - 0.06 * CC - 0.003 * (CC^2) \tag{3}$$

where
n/N: actual to possible sunshine hours
n : number of actual bright sunshine hours
N : number of total possible bright sunshine hours
CC : cloud cover from sunrise to sunset (0-10, 0: cloudless, 10: overcast)

Cloud cover has traditionally been recorded by humans observing the sky. It has been found that humans tend to overestimate local cloud cover especially when lower level clouds and distant clouds are present. Most weather stations are located at airports. Perez et al. (2001) found that the larger the airport, the larger cloud cover overestimation. They hypothesized that the human's tendency to overestimate cloud cover is probably due to air traffic safety concerns. In an effort to reduce these biases, starting in 1990 the National Weather Service has been switching to automated cloud cover measurement using a ceilometer which detects the fraction of clouds detected directly overhead over a 30 minute period.

Correlations between measured daytime total cloud cover and opaque cloud cover versus the ratio between the solar radiation received at the land surface (R_s) and the extraterrestrial radiation received at the top of the atmosphere (R_a) have been developed for Miami International Airport using SAMSON (1961-1985) data. Opaque cloud cover is defined as the amount of the sky covered by clouds that prevent the observation of the sky or of higher cloud layers (i.e. low-level clouds). By relating cloud cover to transmissivity (R_s/R_a) instead of R_s/R_{so} (clear-sky transmissivity), the effects of elevation, solar zenith angle, atmospheric water vapor, dust, aerosol content and sky cover are incorporated into a single relationship. Figure 3 shows that parabolas have been fitted to the cloud cover and solar radiation data. Daytime opaque cloud cover provides a better correlation with transmissivity (R^2 = 0.70) than daytime total cloud cover (R^2=0.58) indicating that low-level clouds have a larger attenuation effect on the solar radiation. When the extraterrestrial radiation signal is incorporated, the R_s estimated using daytime opaque cloud cover similarly exhibits a higher correlation (R^2=0.75) than the estimate using total cloud cover (R^2=0.68) and the lower R_s values are captured better. No significant bias is observed in the estimated R_s at Miami suggesting that the human observations of cloud cover are not significantly biased at this station.

The SAMSON dataset also includes long-term (1961-1990) cloud cover data at West Palm Beach and Key West. Figure 4 shows the correlation between daytime total cloud cover at West Palm Beach and Miami International Airport, both located in the Lower East Coast Area. Although cloud cover at these two stations show some correlation (R^2=0.69), there is a large spread around the regression line as expected. In addition, cloud cover data at these two stations does not span the entire period of record (1965-2000). Cloud cover data is also available at other NOAA stations such as Orlando, Fort Myers and Tampa for relatively short periods of time. No long-term cloud cover data is available for interior stations. Although the correlation between daytime cloud cover and R_s is very strong, currently this method does not represent a feasible alternative for R_s estimation since there is not enough spatially-distributed cloud cover data available for long periods of time.

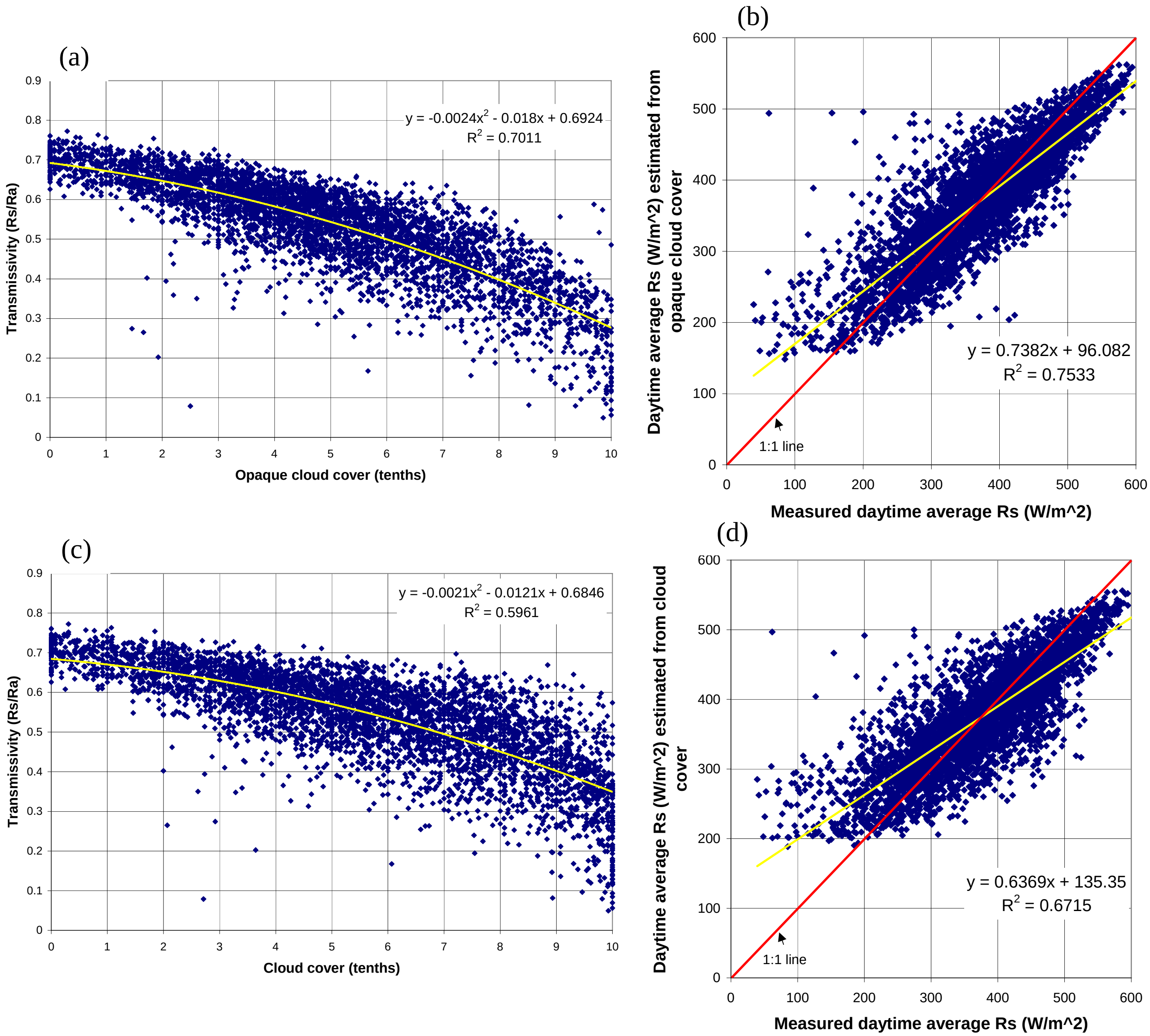


Figure 3. (a) Relationship between daytime opaque cloud cover and transmissivity, (b) Relationship between measured daytime solar radiation and daytime solar radiation estimated from daytime opaque cloud cover, (c) Relationship between daytime cloud cover and transmissivity, (d) Relationship between measured daytime solar radiation and daytime solar radiation estimated from daytime cloud cover.

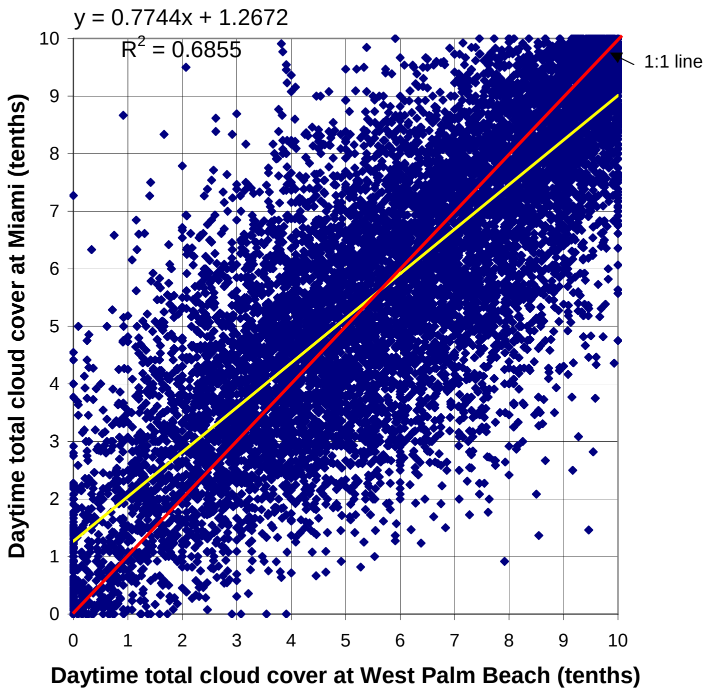


Figure 4. Relationship between daytime total cloud cover at West Palm Beach and Miami International Airport.

2. Self-calibrating (K_r) method:

The Hargreaves and Samani (1982) method (Equation 3), which estimates solar radiation based on the difference between daily maximum and minimum air temperatures, has been used to provide estimates of daily solar radiation in South Florida.

$$R_s = \tau R_a = K_r (T_{\max} - T_{\min})^{0.5} R_a \tag{3}$$

where

R_s	:	solar radiation received at the land surface	[MJ m^{-2} d^{-1}]
τ	:	atmospheric transmissivity	
K_r	:	empirical coefficient	
T_{max}	:	mean daily maximum temperature over the period of interest	[^oC]
T_{min}	:	mean daily minimum temperature over the period of interest	[^oC]
R_a	:	extraterrestrial solar radiation	[MJ m^{-2} d^{-1}]

Since daily temperature can be widely affected by other factors (e.g. proximity to ocean, frontal weather systems, wind speed, evapotranspiration, etc.) the above equation has been recommended for application on timesteps greater than a month (Allen, 1997). On the long-term the difference between daily maximum and minimum temperature is mainly due to changes in cloud cover and can therefore provide a general indication of the amount of solar radiation received at the land surface.

Based on Allen's (1997) self-calibrating method, the empirical coefficient K_r can be determined visually so that the cloud of daily solar radiation estimates plotted by Julian day falls below an envelope given by the clear-sky solar radiation (R_{so}) (Equation A-18). The self-calibrating method (K_r method) for estimating K_r is more accurate when site-specific information about R_{so} is available and when the period of record is long enough such that the probability of a cloudless day increases. The clear-sky transmissivity (τ_o) is a function of elevation, solar zenith angle, atmospheric water vapor, atmospheric dust and aerosol content. It usually varies between around 0.7 and 0.8. Since data is usually not available to determine the site-specific annual variation of τ_o, a constant value is usually used throughout the year. Where no local values are available, FAO (Smith, 1991) recommends using 0.75 as recommended by Doorenbos and Pruitt (1977). Other recommended values found in the literature are: 0.71 by Black et al. (1954) and 0.73 by Penman (1948).

Figure 5 shows estimates of daily average R_s at Miami International Airport (SAMSON 1961-1990) based on the K_r method. A K_r coefficient of 0.20 was determined visually by trying to fit most of the R_s estimates under the clear-sky solar radiation envelope. Given that a constant clear-sky transmissivity of 0.75 has been assumed throughout the year, some values exceed the assumed clear-sky envelope. However, K_r=0.20 was chosen since it minimizes the sum of the errors squared between the measured and the estimated R_s.

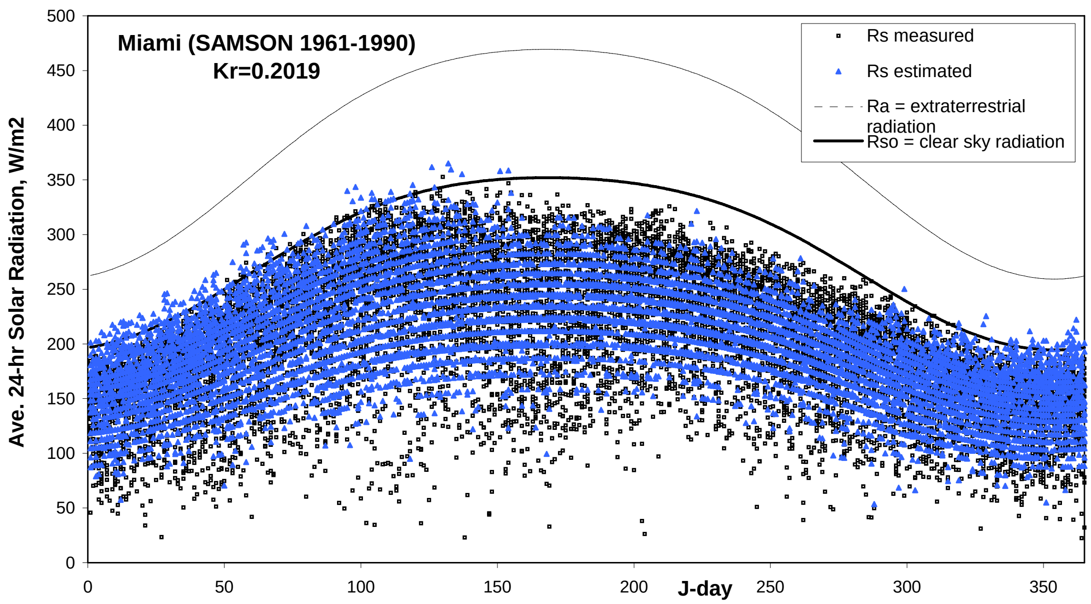


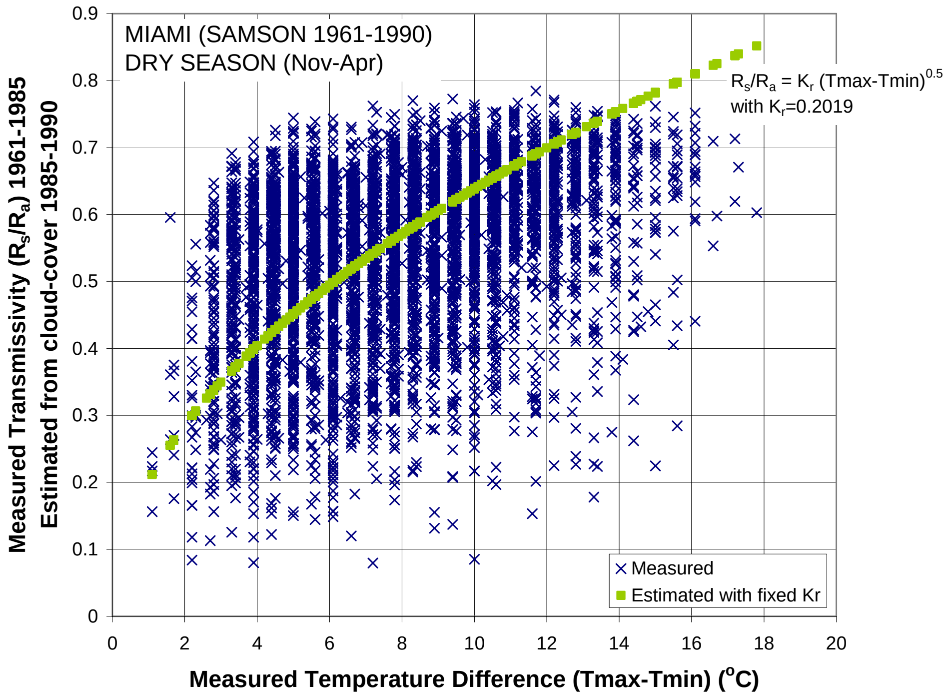
Figure 5. Measured and estimated solar radiation by the K_r method at Miami International Airport (SAMSON 1961-1990) plotted as a function of Julian Day.

Figure 6 shows that for any particular temperature difference at Miami Airport, a very large range of transmissivities are possible. The cloud of wet season data has a triangular shape indicating that the relationship between T_{max}-T_{min} and transmissivity is stronger for the largest temperature differences. In other words, during the wet season a large temperature difference is highly indicative of high transmissivity (cloudless conditions), while a small temperature difference can correspond to a wide range of transmissivities. The relationship between daily temperature difference and transmissivity given by the K_r method (K_r=0.20) is also plotted in Figure 6 for reference. It is obvious that the estimation error from the K_r method is smallest for the higher daily temperature differences especially during the wet season.

A larger range in the temperature differences during the dry season can be observed in Figure 6. Therefore, more variability in the estimated transmissivity is expected during the dry season as shown in Figure 7. The largest temperature differences during the dry season are consistent with temperature changes due to cold fronts moving in from the north during winter. These cold fronts have both lower temperatures and higher cloudiness associated with them, with both signals being captured in the temperature data. Therefore, there is not a clear relationship between a large temperature difference and the transmissivity during the dry season (i.e. the cloud of data has more of a trapezoidal shape).

It is important to keep in mind that near surface air temperature can be affected by a variety of local factors in addition to solar radiation (e.g. trapping of longwave radiation by the atmosphere, evapotranspiration, sensible heating) and advection (e.g. cold fronts). Therefore, a weak relationship between daily temperature range and transmissivity is expected. Overall, the daily temperature range captures slightly more of the variability in transmissivity during the dry season (R^2=0.14) compared to the wet season (R^2=0.10), but the correlations are very weak.

When the extraterrestrial radiation signal (R_a) is incorporated as shown in Figure 8, the K_r method explains more of the variability in solar radiation (R^2=0.45 for the dry season, 0.22 for the wet season, 0.40 overall) with the lowest values being significantly overestimated and the highest values being slightly underestimated (Figures 5, 7b, 8, 9). Therefore, it can be concluded that the R_a signal explains most of the variability in solar radiation with the daily temperature difference providing some weak indication of transmissivity. As observed in Figure 7a, R_a varies the most in March and October (spring and fall seasons respectively) with the least variability in winter and summer. Since both the variability in the estimated transmissivity (using Tmax-Tmin) and the variability in R_a are relatively low during June to September, the variability in the estimated solar radiation is very low and significantly underestimated during these months (Figure 7) when the variability of the measured solar radiation is the largest.



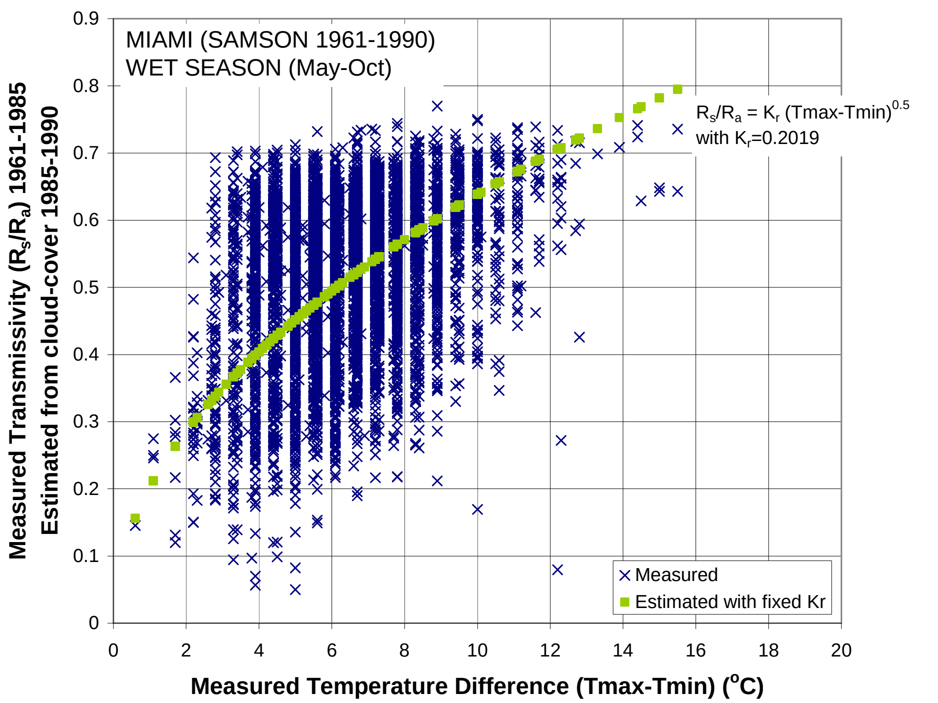


Figure 6. Scatter plots showing relationship between T_{max}-T_{min} and transmissivity at Miami (SAMSON 1961-1990) for the (a) dry and (b) wet seasons. For the period 1961-1985, the "measured" transmissivity was calculated from measured solar radiation. For the period 1985-1990, the "measured" transmissivity was calculated from solar radiation estimated from cloud cover. The transmissivity estimated by the K_r method is plotted for comparison.

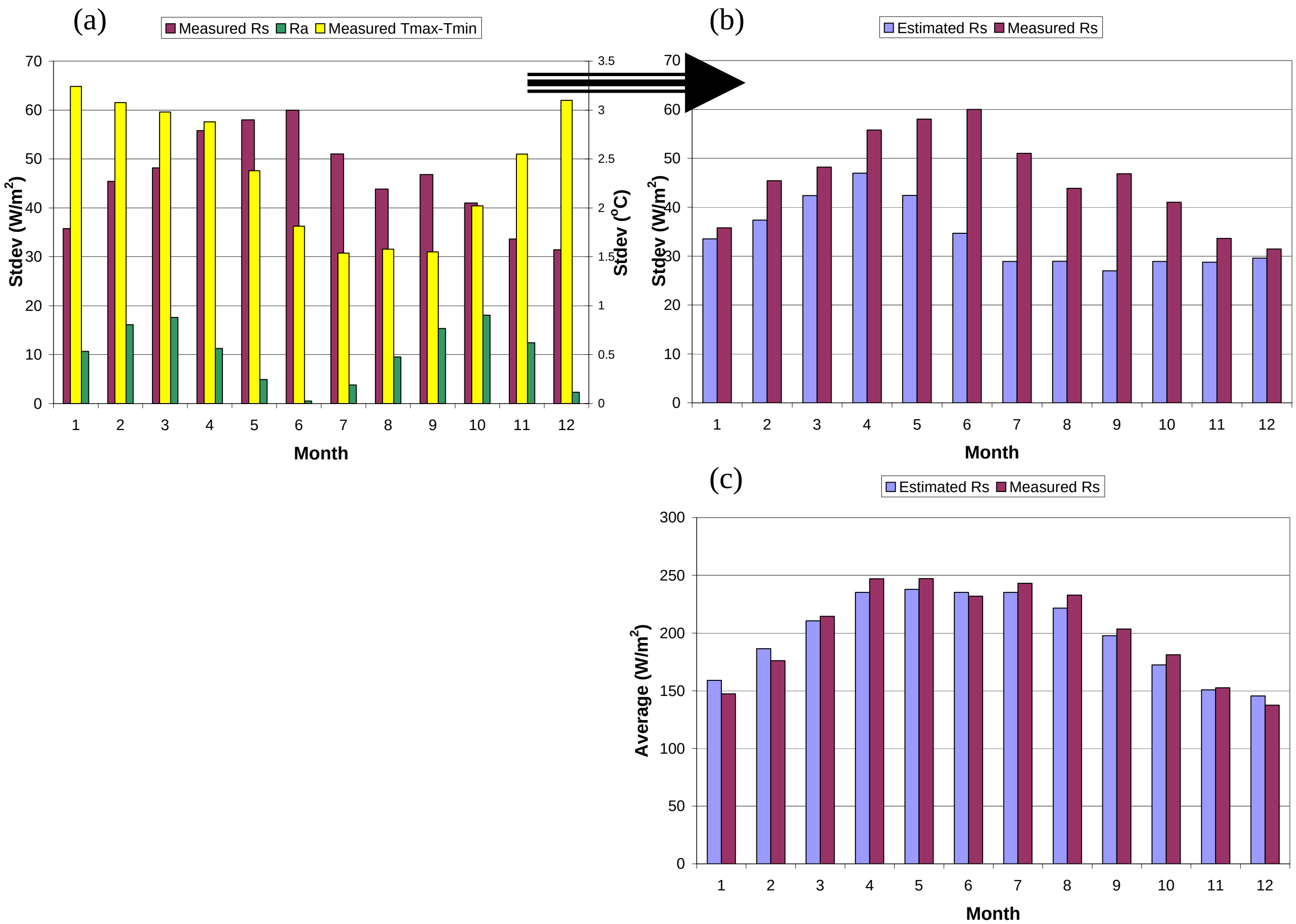
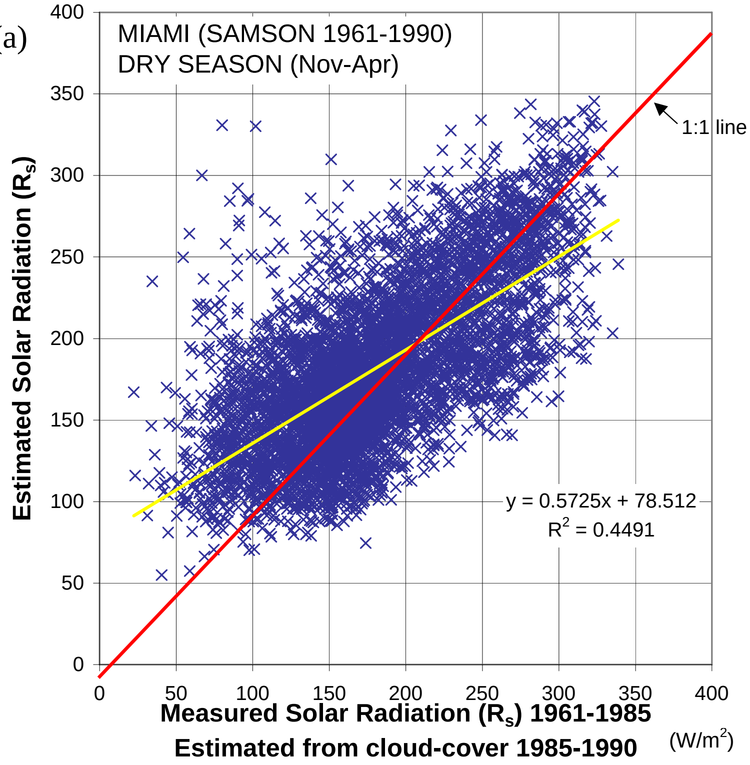


Figure 7. (a) Bar plot comparing the monthly variability (standard deviation) of the measured solar radiation, the extraterrestrial radiation and the measured daily temperature difference at Miami (SAMSON 1961-1990). (b) Bar plot comparing the monthly variability of the measured vs. estimated solar radiation by the K_r method (Overall standard deviation of measured R_s=61.0 W/m^2, overall standard deviation of estimated R_s=48.5 W/m^2). (c) Bar plot comparing the monthly average measured vs. estimated solar radiation by the K_r method (Overall bias=-2.4 W/m^2).

(a)



(b)

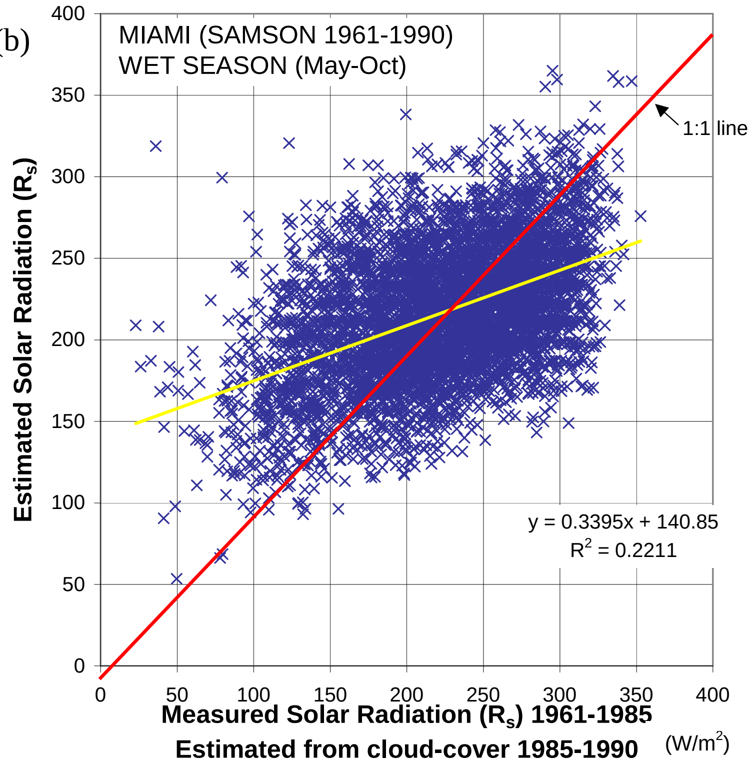


Figure 8. Scatter plots showing comparison between measured vs. estimated solar radiation at Miami (SAMSON 1961-1990) for the (a) dry and (b) wet seasons.

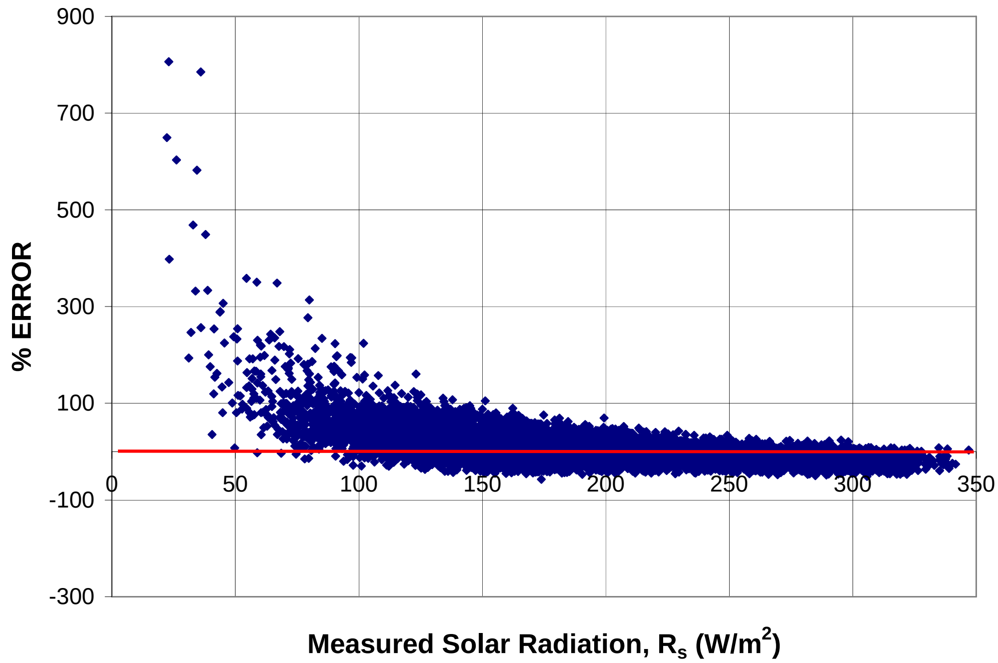


Figure 9. Percentage error in the estimated solar radiation as function of the measured solar radiation for Miami (SAMSON 1961-1990).

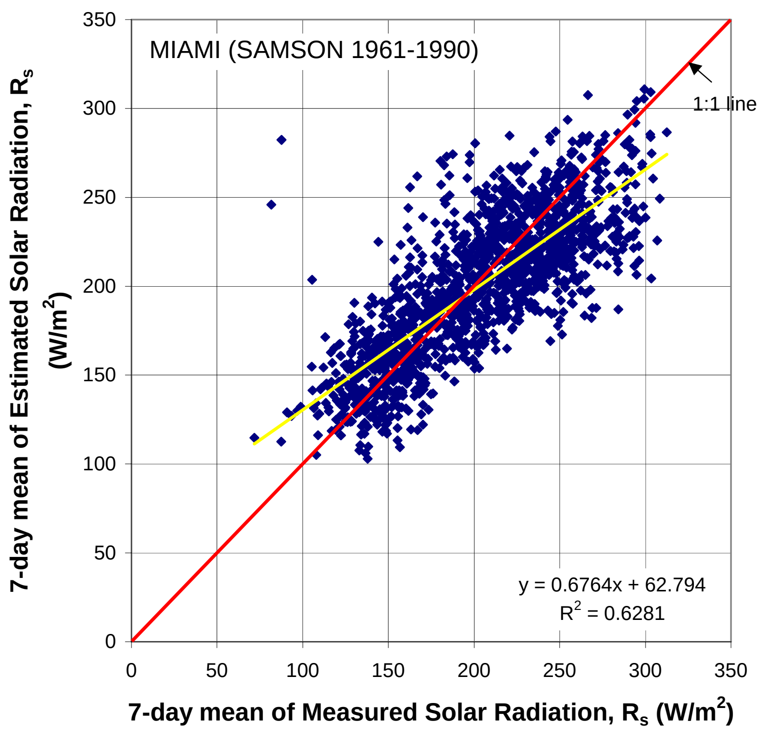


Figure 10. Scatter plot showing comparison between 7-day mean of measured solar radiation vs. 7-day mean solar radiation estimated by the K_r method for Miami (SAMSON 1961-1990).

A two-sided Kolmogorov-Smirnov test was used to determine whether the daily R_s estimated by the K_r method follows the same statistical distribution as the measured R_s. Since the computed K-S-statistic (0.095, i.e. the largest difference between the cumulative distribution functions) is significantly larger than the critical K-S-value (0.026), the null hypothesis that the two datasets have a similar statistical distribution is rejected at a 0.1% level of significance.

Figure 10 shows that there is a larger correlation between the measured and the estimated solar radiation by the K_r method when 7-day means are compared with the coefficient of determination (R^2) increasing to 0.63. The fact that we can be more confident in the performance of the K_r method when averaging over time periods in the order of 7-days, has important implications when interpreting and quantifying uncertainty in hydrologic model output.

The K_r method was applied to several other SAMSON and DBHydro stations (Olthoff, 1999) and in general, the same conclusions can be drawn: the K_r parameter does not vary significantly throughout South Florida, but the method does not capture the statistics of the measured solar radiation reasonably well even after the incorporation of the R_a signal. As shown in Table 2, optimizing for monthly K_r values does not result in any significant improvement in the statistics since the optimal monthly K_r values are very close to the single K_r. Several other temperature-based methods were examined with the hope that a different combination of temperatures would provide a better indication of solar radiation. These will be discussed in the next sections.

3. Variations of the Bristow and Campbell method

The general form of the Bristow and Campbell method (B-C, 1984) for estimating solar radiation is described by Equations 4-5:

$$R_s = R_a \tau_{o(}[1 - \exp(-B \Delta T^C)] \quad (4)$$

where

R_s	:	solar radiation received at the land surface	[MJ m^{-2} d^{-1}]
R_a	:	extraterrestrial solar radiation	[MJ m^{-2} d^{-1}]
τ_o	:	clear-sky transmissivity	
ΔT	:	daily temperature range (T_{max} - T_{min})	[^oC]
T_{max}	:	maximum temperature	[^oC]
T_{min}	:	minimum temperature	[^oC]
C	:	empirical parameter	

$$B = 0.036 \exp(-0.154 \overline{\Delta T}) \quad (5)$$

where

B : empirical parameter

$\overline{\Delta T}$: monthly mean daily temperature range [^oC]

The Campbell-Donatelli (1998) method (C-D, Equations 6-10) for estimating solar radiation was derived from the B-C method:

$$R_s = R_a \tau_{o(}[1 - \exp(-b * f(T_{avg})(\Delta T^2) f(T_{min}))] \tag{6}$$

where
R_s : solar radiation received at the land surface [MJ m^{-2} d^{-1}]
R_a : extraterrestrial solar radiation [MJ m^{-2} d^{-1}]
τ_o : clear-sky transmissivity
b : empirical parameter

$$\Delta T = T_{max,i} - \frac{T_{min,i} + T_{min,i+1}}{2} \tag{7}$$

where
$T_{max,\,i}$: maximum temperature during day i [^oC]
$T_{min,\,i}$: minimum temperature during day i [^oC]

$$f(T_{avg}) = 0.017 * \exp(\exp(-0.053 * T_{avg})) \tag{8}$$

$$T_{avg} = \frac{T_{max,i} + T_{min,i}}{2} \tag{9}$$

$$f(T_{min}) = \exp(T_{min,i} / T_{nc}) \tag{10}$$

where:
T_{nc} : empirical parameter

The only input requirements for C-D are T_{max} and T_{min}. T_{nc} and b are location-specific empirical parameters determined from observed data. The clear-sky transmissivity can be assumed fixed to a certain value, a fixed value can be fitted to the observed data or a function can be defined to describe its variation during the year.

Table 2. Summary statistics of solar radiation estimated by the K_r method using single and monthly K_r values.

a) Miami SAMSON 1961-1990 data:

Obs: Stdev **61.1** Ave **201.3**

	Method	Results of optimization to min(SES) unless noted otherwise:	SES	RMSE	MAE	BIAS	R^2	Stdev	Ave	fraction of values with abs error <10%	<25%	<50%	>100%
1	Kr-Method, single Kr	Kr=0.202	2.54E+07	48.19	37.82	-2.37	0.40	48.5	199.0	0.34	0.71	0.92	0.02
2	Kr-Method, monthly Kr	ave(Kr)=0.200, stdev(Kr)=0.01	2.47E+07	47.50	37.15	-3.07	0.43	52.0	198.3	0.34	0.71	0.92	0.02

b) WPB SAMSON 1961-1990 data:

Obs: Stdev **63.3** Ave **197.7**

	Method	Results of optimization to min(SES) unless noted otherwise:	SES	RMSE	MAE	BIAS	R^2	Stdev	Ave	fraction of values with abs error <10%	<25%	<50%	>100%
1	Kr-Method, single Kr	Kr=0.190	2.26E+07	45.46	36.14	-1.58	0.49	50.7	196.1	0.35	0.70	0.92	0.01
2	Kr-Method, monthly Kr	ave(Kr)=0.188, stdev(Kr)=0.01	2.15E+07	44.34	35.16	-2.64	0.53	55.5	195.1	0.35	0.72	0.93	0.01

c) ENR308 DBHYDRO data:

Obs: Stdev **68.0** Ave **195.9**

	Method	Results of optimization to min(SES) unless noted otherwise:	SES	RMSE	MAE	BIAS	R^2	Stdev	Ave	fraction of values with abs error <10%	<25%	<50%	>100%
1	Kr-Method, single Kr	Kr=0.17	7.08E+06	47.80	38.45	0.31	0.51	47.1	196.2	0.31	0.7	0.88	0.04

d) S65CW DBHYDRO 1992-2002 data:

Obs: Stdev **69.4** Ave **197.5**

	Method	Results of optimization to min(SES) unless noted otherwise:	SES	RMSE	MAE	BIAS	R^2	Stdev	Ave	fraction of values with abs error <10%	<25%	<50%	>100%
1	Kr-Method, single Kr	Kr=0.16	6.29E+06	42.55	33.28	1.35	0.63	49.7	199.4	0.38	0.78	0.89	0.04

e) S331W DBHYDRO 1994-2002 data:

Obs: Stdev **62.7** Ave **185.9**

	Method	Results of optimization to min(SES) unless noted otherwise:	SES	RMSE	MAE	BIAS	R^2	Stdev	Ave	fraction of values with abs error <10%	<25%	<50%	>100%
1	Kr-Method, single Kr	Kr=0.16	5.97E+06	45.54	36.59	-0.17	0.47	44.1	185.5	0.31	0.71	0.89	0.04

Table 3. Summary statistics of solar radiation estimated by different implementations of the Campbell-Donatelli method.

Obs: Stdev Ave
61.1 201.3

Miami SAMSON 1961-1990 data:

	Method	Results of optimization to min(SES) unless noted otherwise:	SES	RMSE	MAE	BIAS	R^2	Stdev	Ave	fraction of values with abs error <10%	<25%	<50%	>100%
1	C-D with Tau fixed=0.74	b=0.31, Tnc=14.15	3.59E+07	57.23	44.09	1.94	0.37	67.0	206.5	0.32	0.63	0.87	0.02
2	C-D with Tau estimated from max Rs/Ra: A=0.74, B=-0.03, C=234	b=0.25, Tnc=12.23	3.49E+07	56.45	43.42	5.73	0.38	66.4	207.1	0.32	0.64	0.88	0.02

Obs: Stdev Ave
63.3 197.7

WPB SAMSON 1961-1990 data:

	Method	Results of optimization to min(SES) unless noted otherwise:	SES	RMSE	MAE	BIAS	R^2	Stdev	Ave	fraction of values with abs error <10%	<25%	<50%	>100%
1	C-D with Tau fixed=0.74	b=0.29, Tnc=15.26	3.41E+07	55.75	43.19	4.21	0.43	70.3	201.9	0.32	0.62	0.86	0.02
2	C-D with Tau estimated from max Rs/Ra: A=0.74, B=-0.03, C=234	b=0.24, Tnc=13.08	3.33E+07	55.13	42.75	4.80	0.44	69.6	202.5	0.32	0.63	0.86	0.02

Obs: Stdev Ave
68.0 195.9

ENR308 DBHYDRO data:

	Method	Results of optimization to min(SES) unless noted otherwise:	SES	RMSE	MAE	BIAS	R^2	Stdev	Ave	fraction of values with abs error <10%	<25%	<50%	>100%
1	C-D with Tau fixed=0.74	b=0.40, Tnc=41.81	7.72E+06	49.92	38.81	-0.53	0.49	60.2	197.3	0.33	0.69	0.9	0.03

Obs: Stdev Ave
69.4 197.5

S65CW DBHYDRO 1992-2002 data:

	Method	Results of optimization to min(SES) unless noted otherwise:	SES	RMSE	MAE	BIAS	R^2	Stdev	Ave	fraction of values with abs error <10%	<25%	<50%	>100%
1	C-D with Tau fixed=0.76	b=0.28, Tnc=37.35	6.18E+06	42.17	32.23	0.81	0.64	61.2	198.7	0.4	0.77	0.91	0.03

Obs: Stdev Ave
62.7 185.9

S331W DBHYDRO 1994-2002 data:

	Method	Results of optimization to min(SES) unless noted otherwise:	SES	RMSE	MAE	BIAS	R^2	Stdev	Ave	fraction of values with abs error <10%	<25%	<50%	>100%
1	C-D with Tau fixed=0.74	b=0.38,Tnc=53.67	6.40E+06	47.14	37.05	-0.08	0.49	58.4	185.5	0.31	0.68	0.9	0.02

Table 3 shows the statistics of solar radiation estimated at several SAMSON and DBHydro stations using C-D. In the first implementation of C-D, a fixed value of clear-sky transmissivity has been assumed during the year. In the second implementation a sinusoidal function of the shape $\tau_o = A + B \cos(2\pi * (\text{Julian day} - C)/365)$ has been fitted to the SAMSON solar radiation data at Miami, West Palm Beach and Key West. It has been found that the parameters A, B and C do not change significantly for these 3 stations. Therefore, a single sinusoidal function with A=0.74, B=-0.03 and C=234 has been used. It is noticed that the two implementations show similar performance. The only advantage of the sinusoidal function is that the observed dip in the clear-sky solar radiation during summer (Figure 11) mainly due to higher humidity is better captured.

A comparison of Tables 2 and 3 shows that the Campbell-Donatelli method captures more of the data variability than the K_r method, with the overall standard deviation of the estimated solar radiation slightly exceeding the overall standard deviation of the measured data. This is clearly noticed by comparing Figures 5, 7, 11 and 12, where C-D is able to capture the full range of solar radiation including the lowest values. The other statistics are comparable to those of the K_r method. However, the Sum of Errors Squared (SES) for Miami and West Palm Beach (SAMSON) is approximately 1.5 times higher with C-D than with the K_r method.

A two-sided Kolmogorov-Smirnov test was used to determine whether the daily R_s estimated by the C-D method with sinusoidal τ function follows the same statistical distribution as the measured R_s at Miami (SAMSON). Since the computed K-S-statistic (0.048, i.e. the largest difference between the cumulative distribution functions) is larger than the critical K-S-value (0.026), the null hypothesis that the two datasets have a similar statistical distribution is rejected at a 0.1% level of significance. However, the fact that the K-S-statistic computed for C-D is much smaller than the K-S-statistic for the K_r method reflects that C-D better reproduces the statistical distribution of the data. This is evident in Figure 13, where quantile-quantile plots of the measured versus the estimated solar radiation are compared for the two methods. In a quantile-quantile plot, values that have the same quantiles (i.e. the percent of data below it) are plotted against each other. The closer the data is to a 45 degree reference line, the stronger the conclusion that the two datasets come from populations with similar distributions. It is clear that the solar radiation estimated by C-D has a more similar statistical distribution to the measured solar radiation than that estimated by the K_r method. However, it is evident from Table 3, that the empirical parameters b and T_{nc} are very site-specific and do not exhibit any clear spatial pattern. Therefore, the K_r method remains a stronger candidate for solar radiation estimation since its single parameter is fairly constant in space.

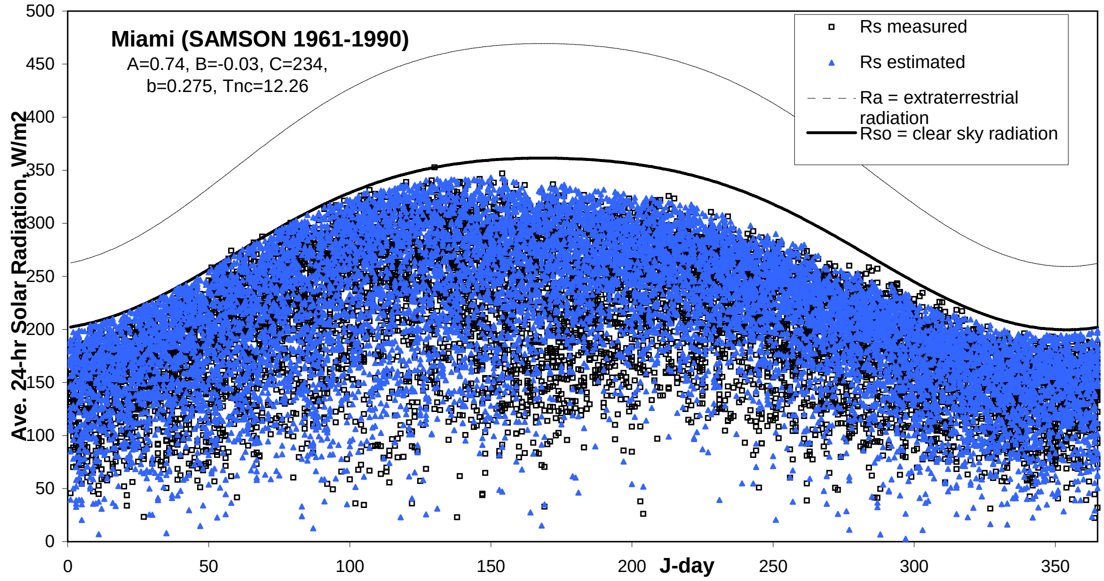


Figure 11. Measured and estimated solar radiation by the Campbell-Donatelli method at Miami International Airport (SAMSON 1961-1990) plotted as a function of Julian Day.

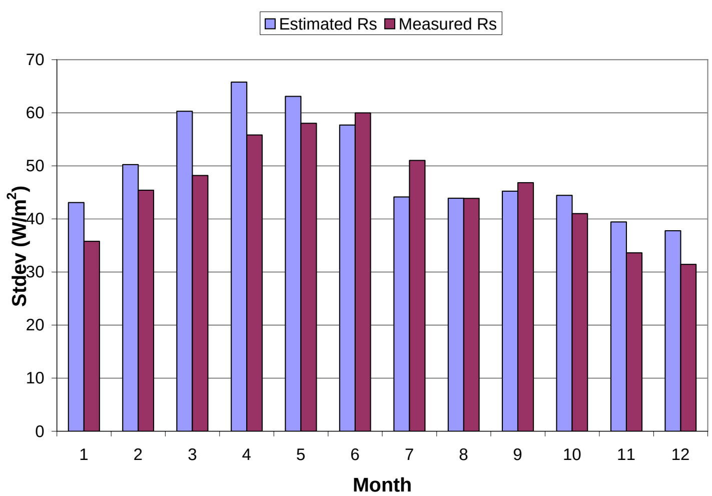


Figure 12. Bar plot comparing the monthly variability of the measured vs. estimated solar radiation by the Campbell-Donatelli method with sinusoidal τ function (Overall standard deviation of measured R_s=61.0 W/m^2, overall standard deviation of estimated R_s=66.4 W/m^2).

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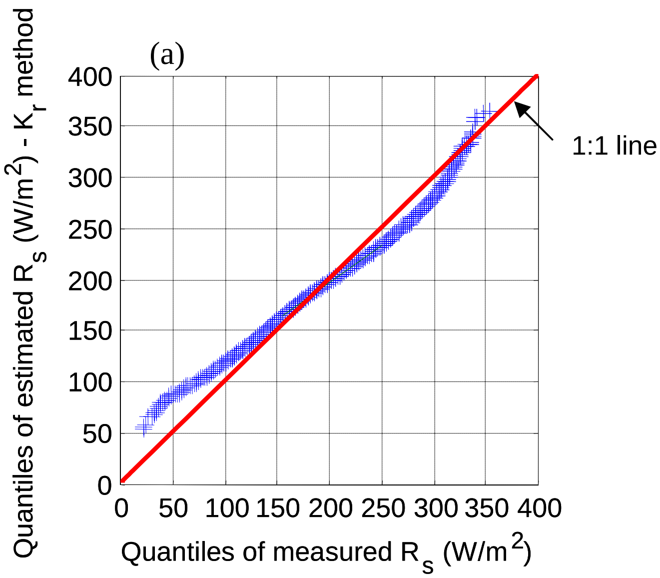
In selecting a solar radiation estimation algorithm for the Variable Infiltration Capacity (VIC: Bowling, 1999) hydrologic model, several implementations of the Bristow and Campbell method were tested. In one of these implementations, the daily change in temperature (ΔT) was reduced on rainy days. We modified C-D to include a reduction in ΔT on rainy days; however, this did not produce any significant improvement in results.

Another variation of Bristow and Campbell is the Thornton and Running method (T-R, 1999). The main features of Thornton and Running are:

- A function relating the clear-sky transmissivity to solar zenith angle, near surface water vapor pressure, and elevation is incorporated.
- A lower bound for the transmissivity is set at 10% of the clear-sky transmissivity.
- A three-parameter exponential decay curve is used to describe B.

Thornton and Running have observed that the highest and lowest values of R_s are predicted very well by their model, with reduced prediction accuracy in the middle range of the observations due to partial cloud cover. In wet climates, where Rs is strongly controlled by variations in clear-sky transmissivity due to high water vapor content and strong variations in cloud cover, their method does not perform very well. For example, the bias and mean absolute error obtained by Thornton and Running for Miami (SAMSON 1961-1985) are significantly larger than those obtained by C-D and the K_r method. Therefore, T-R does not represent a viable alternative for R_s estimation in South Florida. Furthermore, the lack of dew point data also hinders the application of Thornton and Running in South Florida.



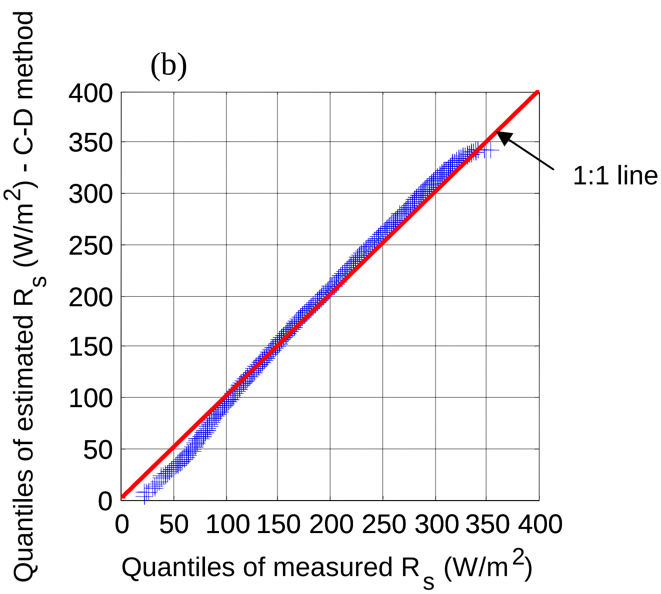


Figure 13. Quantile-quantile plots of (a) measured versus estimated solar radiation by the K_r method, (b) measured versus estimated solar radiation by Campbell-Donatelli for Miami (SAMSON 1961-1990).

4. Modified-K_r method

None of the temperature-based methods examined provided significantly better estimates of solar radiation than the Hargreaves and Samani's K_r method (Equation 3). Since the K_r method requires the estimation of the single parameter (K_r) and since this parameter does not vary significantly across South Florida, the K_r method remained the only viable alternative for R_s estimation. One of the main weaknesses of the K_r method (Equation 3) is its underestimation of the variability in the measured solar radiation. Therefore, we modified the K_r method to increase the variability of R_s by increasing K_r to match the overall standard deviation of the measured R_s. However, since a higher K_r value also results in higher estimates of solar radiation, an additional term was added as a bias correction term:

$$R_s = \tau R_a = R_a K_r (T_{\max} - T_{\min})^{0.5} + B \tag{11}$$

where

R_s	:	solar radiation received at the land surface	[MJ m^{-2} d^{-1} or W/m^2]
τ	:	sky transmissivity	
K_r	:	empirical coefficient	
T_{max}	:	mean daily maximum temperature over the period of interest	[^oC]
T_{min}	:	mean daily minimum temperature over the period of interest	[^oC]
R_a	:	extraterrestrial solar radiation	[MJ m^{-2} d^{-1} or W/m^2]
B	:	empirical term	[MJ m^{-2} d^{-1} or W/m^2]

The above equation was applied to several DBHydro and SAMSON stations. It was found that the effect of the higher K_r was not only to increase the variability of R_s, but it also changed the seasonality of R_s significantly. A monthly-varying B term was applied to correct for seasonality changes. However, it resulted in obvious month to month discontinuities in R_s.

Selected Methods for Solar Radiation and Potential ET Estimation:

Due to its simplicity and accuracy (Abtew, 1996), the Simple Method was selected to provide estimates of long-term historical (1965-2000) *wet marsh potential ET* for long-term hydrological modeling allowing for consistency with the SFWMD DBHydro database. It is important to keep in mind that due to the difference in roughness characteristics between marsh and reference grass surfaces, the crop coefficients developed with respect to a grass-reference ET may need to be modified for use with wet marsh potential ET.

Due to the scarcity of solar radiation and cloud cover data, the self-calibrating K_r method was chosen for estimating R_s for potential ET estimation since it depends on a single parameter with low spatial variability. The K_r method was applied at 17 NOAA stations with long-term (1965-2000) daily temperature data to provide long-term estimates of R_s for hydrologic modeling. For Lake Okeechobee, the average estimated R_s at Canal Point, Moore Haven and Belle Glade was used. The NOAA temperature data was thoroughly checked and patched to correct systematic errors, trends, and missing values with the purpose of producing the best possible temperature dataset for R_s and ET estimation (Lyons, in preparation).

In order to guarantee reasonable estimates the following two constraints were incorporated into the R_s estimation:

- A constant upper bound for the transmissivity is set to 0.75 across South Florida (i.e. clear-sky transmissivity defined as 75% of the extraterrestrial solar radiation).

- A lower bound for the transmissivity is set at 10% of the clear-sky transmissivity.

For each NOAA station, the K_r was selected so that the long-term average annual wet marsh potential ET estimated by the Simple method (Equation 2) matched an expected north to south gradient (Visher and Hughes, 1969). Figure 15 shows that the selected K_r values do not vary significantly from station to station with generally lower values in the interior (e.g. minimum value of 0.154 at Devils Garden) and higher values near the coast (e.g. maximum of 0.210 at Miami International Airport). In general, the selected K_r values agree with Hargreaves' (1994) recommendation of using K_r=0.16 for interior regions and K_r=0.19 for coastal regions. Annual timeseries and summary statistics of wet marsh potential evapotranspiration estimated at 17 NOAA stations and Lake Okeechobee are presented in Table 4.

Previously, the inverse-distance squared method was used to interpolate reference ET (SFWMD, 1999). For the SFWMM2000 update, the TIN method was selected for spatially-interpolating the wet marsh potential ET across a 2-mile x 2-mile resolution super-grid covering most of South Florida (Figure 16). Due to the scarcity of stations where wet marsh potential ET was estimated, it was found that the TIN method results in a smoother spatial variation of potential ET.

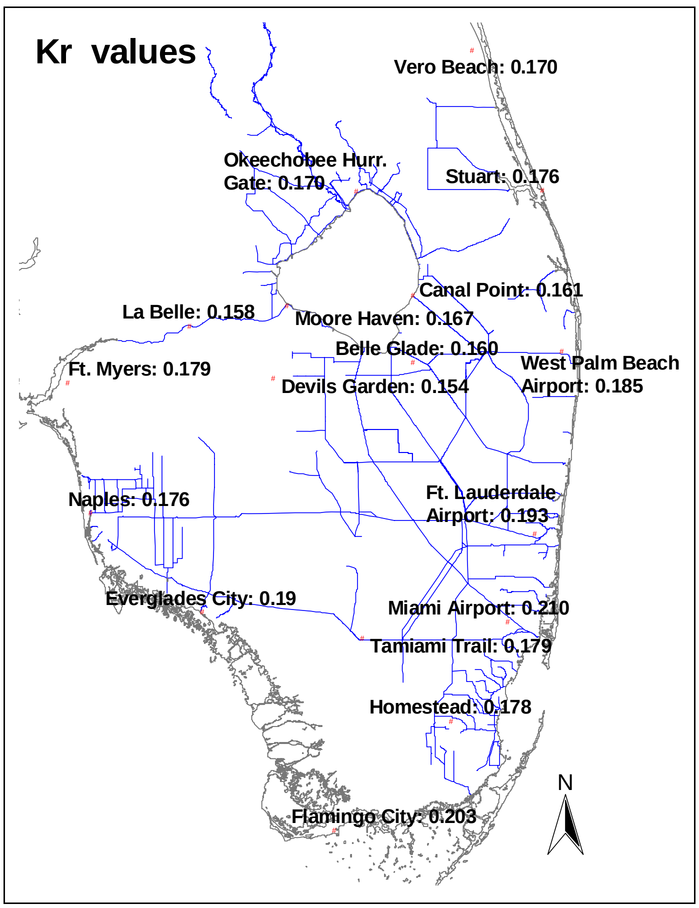


Figure 15. Selected K_r values for 17 NOAA stations with long-term daily temperature data.

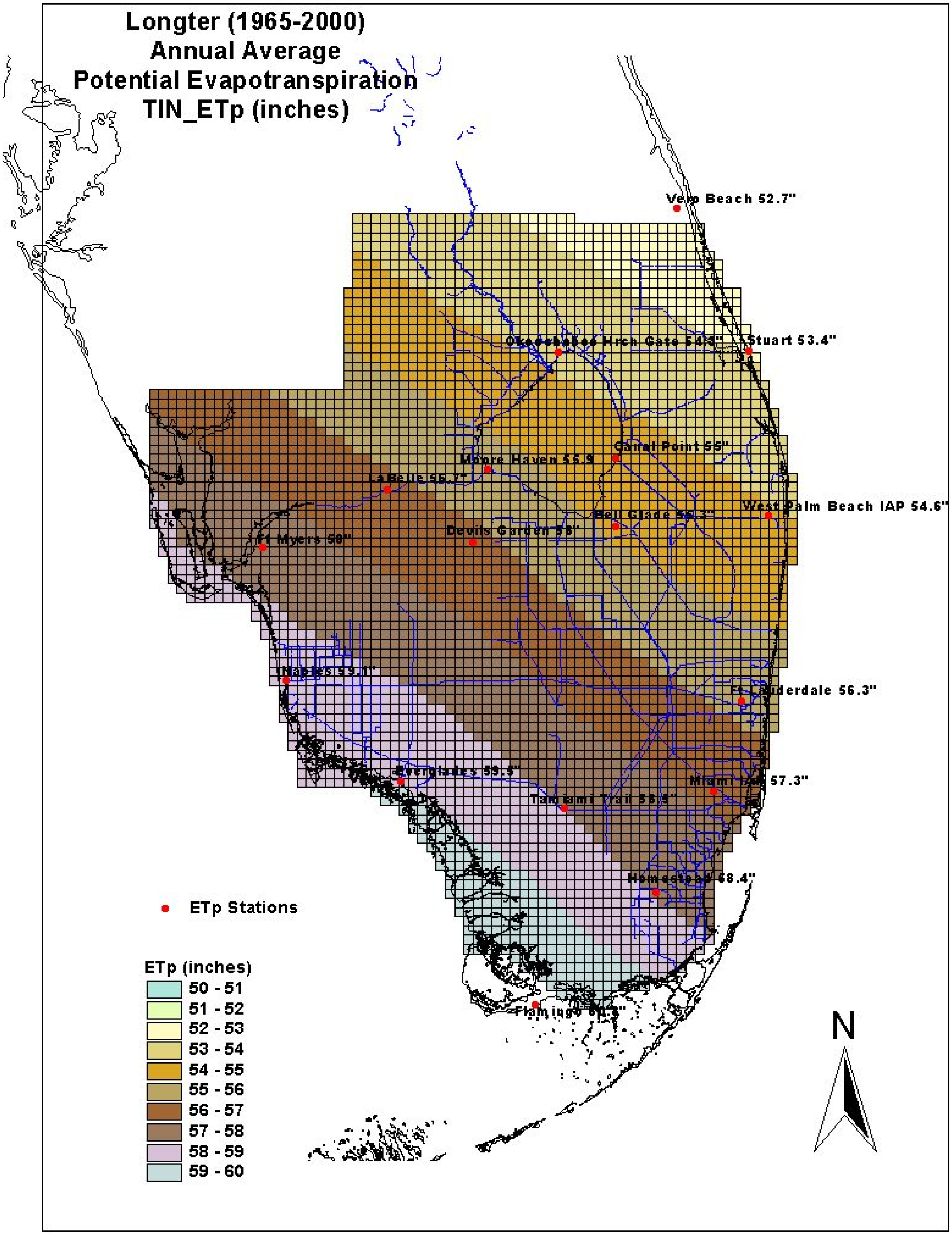


Figure 16. Estimated annual average wet marsh potential evapotranspiration (in/yr) for a 2-mile x 2-mile super-grid which includes the SFWMM and NSM grids.

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Table 4. Annual timeseries and summary statistics of wet marsh potential evapotranspiration estimated at 17 NOAA stations plus Lake Okeechobee.

Year	LOK	La Belle	Devils Garden	Ft Myers	Naples	Everglades City	Flamingo	Homestead	Tamiami Trail	MIA	Ft. Lauderdale	WPBIA	Canal Point	Belle Glade	Moore Haven	Okeechobee Hurr. Gate	Stuart	Vero Beach
Kr	N/A	0.158	0.154	0.179	0.176	0.190	0.203	0.178	0.179	0.210	0.193	0.185	0.161	0.160	0.167	0.170	0.176	0.170
1965	55.27	56.57	54.88	57.96	59.53	62.05	59.58	61.53	60.80	57.74	58.76	55.87	55.16	56.25	54.39	56.14	52.66	52.69
1966	52.74	54.92	53.90	56.94	57.94	60.51	56.77	58.36	56.16	56.85	57.67	53.80	53.13	53.83	51.25	54.77	51.78	52.01
1967	56.58	58.40	55.75	56.46	59.36	60.73	58.52	60.24	63.63	54.76	57.70	57.05	56.86	56.49	56.38	53.21	54.85	54.47
1968	54.57	57.37	54.53	57.70	58.36	60.22	57.89	59.07	59.78	55.59	58.36	56.27	54.31	54.79	54.61	53.97	54.87	53.17
1969	53.03	56.72	53.54	53.86	58.11	60.46	58.24	57.29	56.65	58.07	57.37	53.63	53.77	53.04	52.30	50.78	52.73	50.73
1970	54.75	58.85	55.27	55.86	60.22	58.52	58.93	59.37	53.54	56.73	57.92	54.79	55.18	53.65	55.41	51.84	55.93	52.94
1971	56.90	61.77	58.13	57.34	61.43	60.25	61.70	61.54	61.22	58.62	60.41	57.96	56.89	55.59	58.21	56.08	53.13	53.75
1972	55.60	59.76	56.42	59.32	60.88	58.41	59.34	58.77	58.83	55.98	58.19	54.90	54.34	54.04	58.41	55.23	52.56	52.61
1973	55.71	57.06	56.50	59.23	61.91	60.27	60.01	58.02	59.57	54.62	57.74	54.32	55.03	54.40	57.70	55.47	52.47	51.50
1974	55.95	58.07	57.64	59.90	62.95	60.58	57.60	59.85	60.10	57.24	57.72	53.94	55.66	54.77	57.43	56.04	55.65	53.09
1975	56.29	58.97	56.33	59.61	62.70	58.42	60.72	59.97	59.04	57.45	56.73	54.92	56.09	55.04	57.75	55.73	55.75	54.59
1976	55.38	57.73	57.58	59.14	62.31	60.21	62.08	58.09	56.12	56.63	55.27	54.38	54.92	53.90	57.32	53.63	56.06	54.08
1977	55.66	58.69	56.96	57.89	61.44	59.61	62.38	58.36	57.40	56.14	55.13	55.03	54.66	54.54	57.77	52.47	53.77	53.75
1978	53.65	58.38	53.99	57.57	59.82	59.58	61.30	57.30	55.98	54.80	56.13	55.06	53.85	52.65	54.45	52.95	53.31	53.72
1979	53.84	56.35	54.59	57.93	60.48	57.97	60.21	57.48	58.29	52.95	56.48	54.57	54.01	52.68	54.83	52.07	50.32	52.24
1980	55.30	57.67	55.35	58.56	60.36	58.80	61.83	59.01	59.75	55.86	57.58	57.78	55.20	53.85	56.84	54.41	54.37	54.06
1981	57.27	59.41	59.09	60.05	63.16	60.43	63.72	59.75	62.67	59.88	59.25	57.32	55.96	54.93	60.92	57.32	55.32	55.58
1982	54.03	55.33	52.69	56.76	60.70	57.69	60.75	58.33	60.47	56.36	56.56	50.83	53.31	53.18	55.59	55.91	51.90	50.85
1983	54.50	54.48	53.74	54.26	59.79	57.51	60.58	58.16	57.95	59.52	58.15	52.08	53.43	55.99	54.09	55.69	51.86	52.57
1984	54.58	55.53	54.30	56.73	58.12	60.35	61.41	62.29	56.93	59.23	55.56	52.67	54.25	55.10	54.40	55.00	54.78	50.41
1985	56.16	56.87	59.21	58.30	57.75	60.30	62.75	57.98	61.93	61.09	57.03	54.34	54.33	56.71	57.44	54.11	54.18	51.41
1986	55.96	56.85	55.05	59.85	58.34	61.27	63.42	57.82	57.20	60.40	55.53	54.59	54.87	56.89	56.11	55.00	53.76	54.64
1987	55.65	55.08	55.81	58.74	56.96	60.21	62.85	56.81	56.57	59.10	54.64	53.79	54.00	56.82	56.12	55.25	53.09	53.13
1988	55.65	56.33	59.00	60.61	58.36	63.59	58.07	55.40	57.99	58.80	55.10	53.90	54.60	56.51	55.83	55.00	52.60	52.85
1989	57.94	57.56	59.25	61.41	58.70	56.99	57.89	58.52	64.46	60.38	56.12	55.87	57.08	57.80	58.93	57.62	54.25	54.85
1990	57.10	56.37	57.11	60.83	58.71	56.90	61.55	58.10	63.73	58.41	54.95	54.20	56.64	57.36	57.30	51.22	51.26	52.09

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Year	LOK	La Belle	Devils Garden	Ft Myers	Naples	Everglades City	Flamingo	Homestead	Tamiami Trail	MIA	Ft. Lauderdale	WPBIA	Canal Point	Belle Glade	Moore Haven	Okeechobee Hurr. Gate	Stuart	Vero Beach
Kr	N/A	0.158	0.154	0.179	0.176	0.190	0.203	0.178	0.179	0.210	0.193	0.185	0.161	0.160	0.167	0.170	0.176	0.170
1991	55.58	55.61	57.80	58.12	56.90	59.62	61.47	57.95	59.45	57.54	52.72	53.19	54.81	56.37	55.55	50.10	52.16	51.55
1992	55.38	54.66	57.45	58.23	57.35	57.69	61.20	59.44	59.79	58.21	54.26	54.71	54.61	56.23	55.30	52.79	52.86	53.44
1993	55.87	54.35	57.63	57.82	57.95	60.45	61.48	58.35	54.22	57.55	54.17	53.73	54.58	57.41	55.63	55.49	52.47	53.34
1994	53.90	56.24	58.28	57.11	55.85	59.39	60.74	59.24	56.36	55.41	51.19	54.97	53.30	55.05	53.35	52.68	51.93	51.59
1995	53.80	54.83	61.34	55.46	55.62	58.75	61.79	56.86	54.22	56.58	57.04	57.06	54.32	54.61	52.48	52.53	54.62	51.53
1996	55.72	54.60	61.28	57.27	58.11	62.45	62.67	56.75	58.31	57.51	54.99	53.58	55.46	56.03	55.66	53.70	54.03	51.88
1997	55.32	55.18	58.50	59.45	56.89	59.47	61.30	56.20	57.63	56.56	54.01	52.51	54.94	55.21	55.82	55.58	55.61	49.72
1998	54.67	53.60	58.50	56.51	56.33	56.20	63.82	55.19	56.44	56.20	54.42	53.33	54.86	55.10	54.05	54.62	51.79	51.06
1999	55.71	56.08	58.02	57.63	56.67	57.31	64.79	57.93	56.16	58.08	55.70	54.21	55.67	56.22	55.23	53.94	52.79	52.62
2000	58.19	55.22	56.82	58.85	57.49	58.12	58.63	57.32	56.67	57.53	55.02	53.94	58.24	58.99	57.32	54.81	52.52	53.09
Ann Ave	55.39	56.71	56.73	58.04	59.10	59.48	60.78	58.41	58.50	57.34	56.27	54.59	54.95	55.33	55.89	54.25	53.44	52.71
Stdev	1.25	1.81	2.14	1.71	2.07	1.63	1.98	1.57	2.70	1.81	1.91	1.57	1.16	1.51	1.99	1.78	1.48	1.36
Max	58.19	61.77	61.34	61.41	63.16	63.59	64.79	62.29	64.46	61.09	60.41	57.96	58.24	58.99	60.92	57.62	56.06	55.58
Min	52.74	53.60	52.69	53.86	55.62	56.20	56.77	55.19	53.54	52.95	51.19	50.83	53.13	52.65	51.25	50.10	50.32	49.72
Max-Min	5.45	8.16	8.64	7.56	7.53	7.39	8.02	7.10	10.92	8.14	9.22	7.12	5.12	6.34	9.66	7.52	5.74	5.86

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Appendix A. FAO (Smith, 1991) Guidelines for Estimating Grass-Reference Evapotranspiration Based on the Penman-Monteith Method

$$\lambda ET_o = \frac{\Delta(R_n - G) + \rho c_p (e_a - e_d) 1/r_a}{\Delta + \gamma(1 + r_c / r_a)} \qquad \text{(A-1)}$$

λET_o	:	latent heat flux of evaporation for a standard crop	[kJ m^{-2} s^{-1}]
Δ	:	slope saturated vapor pressure-temperature curve at mean air temperature	[kPa °C^{-1}]
γ	:	psychrometric constant	[kPa °C^{-1}]
R_n	:	net radiation	[kJ m^{-2} s^{-1}]
G	:	soil heat flux	[kJ m^{-2} s^{-1}]
c_p	:	specific heat of moist air	[kJ kg^{-1} °C]
ρ	:	atmospheric density	[kg m^{-3}]
c_p	:	specific heat of moist air	[kJ kg^{-1} °C^{-1}]
e_a	:	saturation vapor pressure at mean air temperature	[kPa]
e_d	:	saturation vapor pressure at dew point temperature (T_{dew})	[kPa]
r_c	:	crop canopy (bulk stomata) resistance	[s m^{-1}]
r_a	:	aerodynamic resistance	[s m^{-1}]

Parameters used in equation above are estimated as follows:

Latent heat of vaporization (λ):

$$\lambda = 2.501 - (2.36\text{E} - 3)T \qquad \text{(A-2)}$$

λ	:	latent heat of evaporation	[MJ kg^{-1}]
T	:	daily mean air temperature	[°C]

Psychrometric Constant (γ):

$$\gamma = 0.00163 \frac{P}{\lambda} \qquad \text{(A-3)}$$

P	:	atmospheric pressure	[kPa]

Specific heat of moist air (c_p):

$$c_p = \gamma \frac{0.622\lambda}{P} \qquad \text{(A-4)}$$

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Saturation vapor pressure (e_a):

$$e_a = 0.5(0.611\exp(\frac{17.27T_{\max}}{T_{\max}+237.3}) + 0.611\exp(\frac{17.27T_{\min}}{T_{\min}+237.3})) \quad \text{(A-5)}$$

Saturation vapor pressure at dew point temperature (e_d):

$$e_d = 0.611\exp(\frac{17.27T_{dew}}{T_{dew}+237.3}) \quad \text{(A-6)}$$

T_{dew}:	point temperature	[°C]

Atmospheric density (ρ):

$$\rho = \frac{1000P}{T_{kv}R} = 3.486\frac{P}{T_{kv}} \quad \text{(A-7)}$$

R :	Specific gas constant = 287	[J kg^{-1} K^{-1}]
T_{kv} :	Virtual temperature	[K]

Virtual temperature (T_{kv}):

$$T_{kv} = T_k(1-0.378\frac{e_d}{P})^{-1} \quad \text{(A-8)}$$

T_k :	daily mean air temperature	[K]

Slope vapor pressure curve (Δ):

$$\Delta = \frac{4098e_a}{(T+237.3)^2} \quad \text{(A-9)}$$

T :	daily mean air temperature	[°C]

Soil heat flux (G):

$$G = c_s d_s(\frac{T_n - T_{n-1}}{\Delta t}) \quad \text{(A-10)}$$

G :	soil heat flux	[MJ m^{-2} d^{-1}]
T_n :	mean temperature on day (or month) n	[°C]
T_{n-1}:	mean temperature on previous day (or month) n-1	[°C]
Δt :	length period	[d]

c_s : soil heat capacity = 2.1 [MJ m^{-3} °C^{-1}]
d_s : estimated effective soil depth = 0.18 for daily temperature fluctuations (Wright and Jensen, 1972) [m]

Aerodynamic resistance (r_a):

$$r_a = \frac{\ln\left(\frac{z_m - d}{z_{om}}\right).\ln\left(\frac{z_h - d}{z_{oh}}\right)}{k^2 U_z} \qquad \text{(A-11)}$$

r_a : aerodynamic resistance [s m^{-1}]
z_m : height of wind speed measurements [m]
z_h : height of temperature and humidity measurements [m]
k : von Karman Constant = 0.41
U_z : wind speed at height z_m [m s^{-1}]
d : zero plane displacement of wind profile = 0.08 [m]
z_{om} : roughness parameter for momentum = 0.015 [m]
z_{oh} : roughness parameter for heat and water vapor = 0.0015 [m]

Crop canopy resistance (r_c):

$$r_c = \frac{R_l}{0.5LAI} = \frac{200}{LAI} \qquad \text{(A-12)}$$

R_l : average 24-hour stomata resistance of single leaf = 100 [s m^{-1}]
LAI: leaf area index = 24 h_c for clipped grass

For reference crop, h_c = 0.12, hence LAI = 2.88 and r_c = 70 [s m^{-1}].

Relative distance from the sun to the earth (d_r):

$$d_r = 1 + 0.033\cos\left(\frac{2\pi J}{365}\right) \qquad \text{(A-13)}$$

J : Julian day of the year

Declination of the sun (δ):

$$\delta = 0.409\sin\left(\frac{2\pi J}{365} - 1.39\right) \qquad \text{(A-14)}$$

Sunset hour angle (ω_s):

$$w_s = \arccos(\tan\varphi \tan\delta) \qquad \text{(A-15)}$$

δ	:	declination of sun	[rad]
φ	:	station latitude	[rad]

Extraterrestrial solar radiation (R_a):

Extraterrestrial radiation can be calculated from latitude and time of year by integrating the instantaneous radiation intensity at the outer atmosphere from sunrise to sunset in

$$R_a = \frac{24*60}{\pi} G_{sc} d_r (\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s) \quad \text{(A-16)}$$

Ra	:	extraterrestrial solar radiation	[MJ m^{-2} d^{-1}]
G_{sc}	:	solar constant = 0.8202 (Duffie and Beckman, 1991)	[MJ m^{-2} min^{-1}]

Net shortwave radiation (R_{ns}):

Net shortwave radiation is the solar radiation received by the surface taking into account losses due to reflection.

$$R_{ns} = (1-\alpha) R_s \quad \text{(A-17)}$$

R_{ns}	:	net shortwave solar radiation (shortwave)	[MJ m^{-2} d^{-1}]
α	:	albedo or canopy reflection coefficient = 0.23 overall average for grass	
R_s	:	incoming solar radiation (shortwave)	[MJ m^{-2} d^{-1}]

Clear-sky shortwave radiation (R_{so}):

$$R_{so} = \tau_o R_a = (a_s + b_s) R_a \quad \text{(A-18)}$$

R_{ns}	:	cloudless shortwave solar radiation (shortwave)	[MJ m^{-2} d^{-1}]
τ_o	:	clear-sky transmissivity = a_s + b_s	

Angstrom values, a_s = 0.23 and b_s = 0.48 reported by Black et al. (1954) for world wide locations were used.

Cloudiness adjustment factor (f_{cl}):

$$` f_{cl} = a_c \frac{R_s}{R_{so}} + b_c \quad \text{(A-19)}$$

where a_c = 1.35 and b_c =0.35 as recommended by FAO (1977).

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Net Emissivity (e'):

$$e' = 0.34 - 0.14\sqrt{e_d} \quad \text{(A-20)}$$

Net long-wave radiation (R_{nl}):

Net longwave radiation is the difference between thermal radiation from vegetation and soil to the atmosphere and reflected radiation from the atmosphere and clouds, and can be estimated using:

$$R_{nl} = f_{cl}(e')\sigma T_k^4 \quad \text{(A-21)}$$

R_{nl} :	net long-wave radiation	[MJ m^{-2} d^{-1}]
T_k :	daily mean air temperature	[K]

Net radiation (R_n):

Net absorbed radiation is the difference between absorbed incoming shortwave solar radiation and net outgoing long-wave radiation.

$$R_n = R_{ns} - R_{nl} \quad \text{(A-22)}$$

R_{nl} :	net radiation	[MJ m^{-2} d^{-1}]

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Appendix B. Sources of wind speed data for South Florida.

GSOD (Global Summary of the Day): Standard measurement height: 33 ft, but heights vary from 20-40 ft		
Station	*WMO ID*	*Period of record*
Homestead AFB	722026	1994-2000
Fort Lauderdale - Hollywood	722025	1994-2000
Fort Myers	722108	1994-2000
Lake Worth	994050	1994-1996
Miami Intl. Airport	722020	1994-2000
Miami-Kendall/Tamiami	722029	1994-2000
Tampa Intl. Airport	722110	1994-2000
West Palm Beach Intl. Airport	722030	1994-2000

SAMSON (Solar and Meteorological Surface Observation Network, NREL, 1993): Measurement height changes by station and by date as tower location is changed.		
Station	*Tower height (ft)*	*Period of record*
Miami	23	1965-present
West Palm Beach	22	1965-1986
	33	1986-present

SFWMD DBHydro: Standard measurement height: 33 ft. Wind speed data is available for additional stations, but the period of record is usually less than 10 y ears.		
Station	*DBKey*	*Period of record*
BELLE GL	DO524	1996-present
CFSW	15509	1992-present
ENR105	15852	1994-1999
ENR308	15879	1994-present
LOXWS	DU558	1993-present
ROTNWX	GE345	1997-present
S140W	15498	1992-2002
S5A_WIND	15104	1985-2000
S78W	15487	1992-present
L3BRS	F9559	1996-1998
S331W	16253	1994-present
S7WX	GG621	1998-present